

$D\bar{D}$ and DD pair production at the LHCb in the parton Reggeization approach

A.V. Karpishkov^{*†}

Samara National Research University, Moscow Highway, 34, 443086, Samara, Russia

E-mail: karpishkov@rambler.ru

M.A. Nefedov

Samara National Research University, Moscow Highway, 34, 443086, Samara, Russia

E-mail: nefedovma@gmail.com

V.A. Saleev

Samara National Research University, Moscow Highway, 34, 443086, Samara, Russia

E-mail: saleev@samsu.ru

A.V. Shipilova

Samara National Research University, Moscow Highway, 34, 443086, Samara, Russia

E-mail: alexshipilova@samsu.ru

We study the inclusive $D\bar{D}$ and DD pair production in proton-proton collisions at the LHC at leading order of the parton Reggeization approach endowed with universal scale-depended fragmentation functions for c -quark to D -meson and for gluon to D -meson transitions. We have described $D\bar{D}$ and DD distributions in azimuthal angle, as well as transverse momentum, rapidity distance, and invariant mass measured in the region of large rapidity $2 < y < 4$ by the LHCb Collaboration at the LHC without free parameters. We have used Reggeized amplitudes for the processes $RR \rightarrow gg$ and $RR \rightarrow c\bar{c}$ which are obtained accordingly to Feynman rules of the L.N. Lipatov effective theory of Reggeized partons, and Kimber-Martin-Ryskin model for unintegrated gluon distribution function in a proton with Martin-Stirling-Thorne-Watt collinear parton distributions as inputs.

XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects

11-15 April, 2016

DESY Hamburg, Germany

^{*}Speaker.

[†]The work of A. V. Karpishkov, M.A. Nefedov, V.A. Saleev and A. V. Shipilova was supported in part by the Russian Foundation for Basic Research through the Grant No. 14-02-00021.

1. Introduction

The study of the D -meson production at high energies provides a crucial test of the next-to-leading order (NLO) calculations in perturbative quantum chromodynamics (QCD) due to the smallness of strong coupling constant $\alpha_s(\mu)$, as the lowest limit of typical energy scale of the hard interaction μ is controlled by the charm quark mass $m \gg \Lambda_{QCD}$, where Λ_{QCD} is the asymptotic scale parameter of QCD. At the same time, we achieve a new dynamical regime, *Regge limit*, where $\sqrt{s} \gg \mu \gg \Lambda_{QCD}$ and the large coefficients of new type $\log^n(\sqrt{s}/\mu)$ should be resummed in all-order terms of perturbative QCD series, introducing a new small parameter $x = \mu/\sqrt{s}$. For this purpose we develop the k_T -factorization framework [1, 2, 3] endowed with the fully gauge-invariant amplitudes with *Reggeized* gluons in the initial state and call this combination the Parton Reggeization Approach (PRA).

Recently, we demonstrated the advantages of the PRA in studies of bottom-flavored jets [4, 5], charmonium and bottomonium production [6, 7, 8, 9, 10], inclusive production of single jet [11], pair of jets [12], prompt-photon [13, 14], photon plus jet [15], Drell-Yan lepton pairs [16].

2. Basic Formalism

We study the pair production of D -mesons with high transverse momenta using the factorization theorem of QCD for the $D\bar{D}$ -cross section:

$$\frac{d\sigma(p + p \rightarrow D_i(p_D) + \bar{D}_j(p_{\bar{D}}) + X)}{dp_{TD}dy_D dp_{T\bar{D}}dy_{\bar{D}}} = \sum_{i,j} \int_0^1 \frac{dz_1}{z_1} D_{i \rightarrow D}(z_1, \mu^2) \int_0^1 \frac{dz_2}{z_2} D_{j \rightarrow \bar{D}}(z_2, \mu^2) \times \frac{d\sigma(p + p \rightarrow i(p_i) + j(p_j) + X)}{dp_{iT}dy_i dp_{jT}dy_j}, \quad (2.1)$$

where $D_{i \rightarrow D}(z, \mu^2)$ is the fragmentation function (FF) for producing the D -meson from the parton i , created at the hard scale μ , the fragmentation parameter z is defined through the relation $p_i = p_D/z$, with p_D and p_i to be D -meson and i -parton four-momenta, correspondingly, and their rapidities $y_D = y_i$. In our calculations we use the LO FFs from Ref. [17], where the fits of nonperturbative D^0 , D^+ , D^{*+} , and D_s^+ FFs, both at LO and NLO in the \overline{MS} factorization scheme, to OPAL data from LEP1 [18] were performed. These FFs satisfy two desirable properties: at first, their μ -scaling violation is ruled by DGLAP evolution equations; at second, they are universal. It was shown in Ref. [19], that the significant part of D -mesons is produced through the gluon and charm quark fragmentation only.

At large \sqrt{s} the dominant contributions to cross sections of QCD processes gives multi-Regge kinematics (MRK), where all particles have limited (not growing with \sqrt{s}) transverse momenta and are combined into jets with limited invariant mass of each jet and strongly separated in rapidities. At leading logarithmic approximation of the Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach [20] which gives the description of QCD scattering amplitudes in this region, where the logarithms of type $(\alpha_s \log(1/x))^n$ are resummed, only gluons can be produced and each jet is actually a gluon. At next-to-leading logarithmic approximation (NLA) the terms of $\alpha_s(\alpha_s \log(1/x))^n$ are collected and a jet can contain a couple of partons (two gluons or quark-antiquark pair) with close rapidities.

Such kinematics is called quasi multi-Regge kinematics (QMRK). Despite of a great number of contributing Feynman diagrams it turns out that at the Born level in the MRK amplitudes acquire a simple factorized form. Moreover, radiative corrections to these amplitudes do not destroy this form, and this phenomenon is called gluon Reggeization [21]. The full set of the induced and effective vertices of Reggeon-particle interactions together with Feynman rules was written in Refs. [22] and [23]. The effective action which includes the fields of Reggeized gluons [24] and Reggeized quarks [23] was introduced and the non-Abelian gauge invariant theory was developed.

The lowest order in α_s parton subprocesses of the PRA in which gluon or c -quark pair is produced are: a quark-antiquark pair production $\mathcal{R} + \mathcal{R} \rightarrow c + \bar{c}$ and the corresponding gluon pair production in QMRK via two Reggeized gluons fusion $\mathcal{R} + \mathcal{R} \rightarrow g + g$. We present the amplitudes of these processes and their matrix elements squared in the work [12].

In the k_T -factorization, differential cross section for the $2 \rightarrow 2$ subprocess has the form:

$$\frac{d\sigma}{dy_1 dy_2 dp_{1T} dp_{2T} d\Delta\phi} (p + p \rightarrow c(p_1) + \bar{c}(p_2) + X) = \frac{p_{1T} p_{2T}}{16\pi^3} \int d\phi_1 \int dt_1 \times \\ \times \Phi(x_1, t_1, \mu^2) \Phi(x_2, t_2, \mu^2) \frac{|\mathcal{M}(\mathcal{R} + \mathcal{R} \rightarrow c + \bar{c})|^2}{(x_1 x_2 S)^2}, \quad (2.2)$$

where ϕ_1 is the azimuthal angle between \mathbf{p}_T and \mathbf{q}_{1T} and $\Delta\phi$ is the azimuthal angle between \mathbf{p}_{1T} and \mathbf{p}_{2T} . The unintegrated over transverse momenta parton distribution functions (UPDFs) $\Phi(x, t, \mu^2)$ depend on Reggeon transverse momentum \mathbf{q}_T while its virtuality is $t = -|\mathbf{q}_T|^2$. The UPDFs are defined to be related with collinear ones through the equation $xG(x, \mu^2) = \int^{\mu^2} dt \Phi(x, t, \mu^2)$. We obtain the UPDFs using the model of Kimber, Martin and Ryskin [25, 26] where the transverse momentum of a parton in the initial state of the hard scattering comes entirely from the last step of evolution cascade, and the parton radiated at the last step is ordered in rapidity with the particles produced in the hard subprocess.

3. Results

We compare the experimental data for $D\bar{D}$ -mesons produced at the collision energy of $\sqrt{S} = 7$ TeV at rapidity range $2.0 < y < 4.0$ [27], with our predictions in the LO of the PRA, in the Fig. 1. The green lines represent contributions of the c -quark fragmentation while blue lines correspond to the gluon ones, and their sum is shown as a solid line. A theoretical uncertainty is estimated by varying factorization and renormalization scales between $1/2m_T$ and $2m_T$ around their central value of m_T , the transverse mass of a fragmenting parton. The resulting uncertainty is depicted in the figures by shaded bands. The analogous comparison of the recent data from the LHCb at $\sqrt{S} = 7$ TeV for DD mesons [27] is presented in the Fig. 2. Here we take into account only $\mathcal{R} + \mathcal{R} \rightarrow g + g$ contribution because in final state we have only D and D mesons, but don't have \bar{D} mesons. We find a good agreement between our predictions and experimental data for the different distributions of D -meson pairs within experimental and theoretical uncertainties.

4. Conclusions

In the present work we performed the study of D -meson pair production in proton-proton collisions at the region of large rapidities as it is implemented for the LHCb detector in the framework

of Parton Reggeization Approach. Here we take into account all the hard-scattering parton subprocesses appearing at the LO with Reggeized gluons in the initial state. To describe the hard scattering stage we use the fully gauge invariant amplitudes introduced in the works of L. N. Lipatov and co-authors. The distributions of initial partons are taken in the form of UPDFs proposed by Kimber, Martin and Ryskin, and the way of their definition is ideologically related to the above-mentioned amplitudes. We obtained a good agreement of our results for pair D -meson production comparing with experimental data from the LHC, especially at large transverse momenta. The achieved degree of agreement is the same as the one obtained by NLO calculations in the conventional collinear parton model. We also have a good description of the azimuthal distributions at the LO of the PRA in contrast to the collinear parton model. We can see that pair DD production is described very well just by the subprocess $\mathcal{R} + \mathcal{R} \rightarrow g + g$. This fact in addition to result of $D\bar{D}$ production indicates that there is no any necessity to involve the hypothesis of double parton scattering [28], see also talk of Prof. Szczurek [29]. We describe D -meson production without any free parameters or auxiliary approximations.

References

- [1] J. C. Collins, R. K. Ellis, Nucl. Phys. B **360**, 3 (1991).
- [2] L. V. Gribov, E. M. Levin, M. G. Ryskin, Phys. Rept. **100**, 1 (1983).
- [3] S. Catani, K. M. Ciafaloni, F. Hautmann, Nucl. Phys. B **366**, 135 (1991).
- [4] B. A. Kniehl, A. V. Shipilova, and V. A. Saleev, Phys. Rev. D **81**, 094010 (2010).
- [5] V. A. Saleev, A. V. Shipilova Phys. Rev. D **86**, 034032 (2012).
- [6] B. A. Kniehl, V. A. Saleev, D. V. Vasin, Phys. Rev. D **73**, 074022 (2006).
- [7] B. A. Kniehl, V. A. Saleev, and D. V. Vasin, Phys. Rev. D **74**, 014024 (2006).
- [8] V. A. Saleev and D. V. Vasin, Phys. Rev. D **68**, 114013 (2003); Phys. Atom. Nucl. **68**, 94 (2005) [Yad. Fiz. **68**, 95 (2005)].
- [9] M. A. Nefedov, V. A. Saleev, A. V. Shipilova, Phys. Rev. D **85**, 074013 (2012).
- [10] M. A. Nefedov, V. A. Saleev, A. V. Shipilova, Phys. Rev. D **88**, 014003 (2013).
- [11] B. A. Kniehl, V. A. Saleev, A. V. Shipilova, E. V. Yatsenko, Phys. Rev. D **84**, 074017 (2011).
- [12] M. A. Nefedov, V. A. Saleev, A. V. Shipilova, Phys. Rev. D **87**, 094030 (2013).
- [13] V. A. Saleev, Phys. Rev. D **78**, 034033 (2008). [arXiv:0807.1587 [hep-ph]];
- [14] V. A. Saleev, Phys. Rev. D **78**, 114031 (2008).
- [15] B. A. Kniehl, M. A. Nefedov, V. A. Saleev, Phys. Rev. D **89**, 114016 (2014).
- [16] M. A. Nefedov, N. N. Nikolaev, V. A. Saleev, Phys. Rev. D **87**, 014022 (2013).
- [17] B. A. Kniehl and G. Kramer, Phys. Rev. D **74**, 037502 (2006).
- [18] K. Ackerstaff *et al.* [OPAL Collaboration], Eur. Phys. J. C **1**, 439 (1998); G. Alexander *et al.* [OPAL Collaboration], Z. Phys. C **72**, 1 (1996).
- [19] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, Phys. Rev. Lett. **96**, 012011 (2006).

- [20] E. A. Kuraev, L. N. Lipatov, V. S.Fadin, Sov. Phys. JETP **44**, 443 (1976). [in Russian]; I. I. Balitsky, L. N. Lipatov, Sov. J. Nucl. Phys. **28**, 822 (1978). [in Russian].
- [21] E. A. Kuraev, L. N. Lipatov, V. S.Fadin, Phys. Lett. B **60**, 50 (1975).
- [22] E. N. Antonov, L. N. Lipatov, E. A. Kuraev, I. O. Cherednikov, Nucl. Phys. B **721**, 111 (2005).
- [23] L. N. Lipatov, M. I. Vyazovsky, Nucl. Phys. B **597**, 399 (2001).
- [24] L. N. Lipatov, Nucl. Phys. B **452**, 369 (1995).
- [25] M. A. Kimber, A. D. Martin, M. G. Ryskin, Phys. Rev. D **63**, 114027 (2001).
- [26] G. Watt, A. D. Martin, M. G. Ryskin, Eur. Phys. J. C **31**, 73 (2003).
- [27] R. Aaij *et al.* [LHCb Collaboration], JHEP **1206**, 141 (2012).
- [28] R. Maciula, A. Szczurek, V. A. Saleev and A. V. Shipilova, Phys. Lett. B **758**, 458 (2016).
- [29] A. Szczurek, in proceedings of "24th International Workshop on Deep-Inelastic Scattering and Related Subjects", PoS(DIS2016)126.

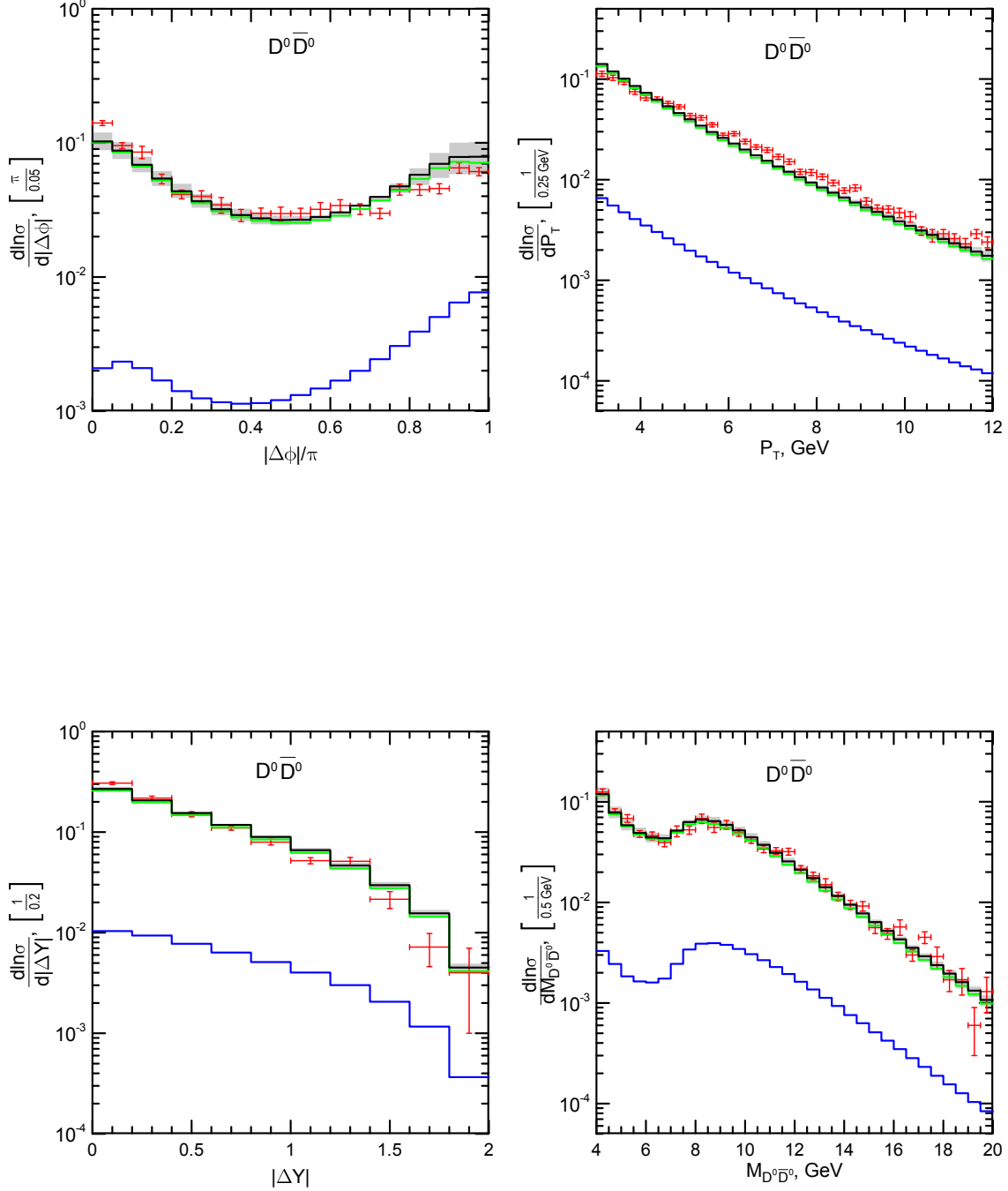


Figure 1: Distributions in azimuthal angle between D^0 and \bar{D}^0 mesons (left-top); in transverse momentum of D^0 (right-top); in rapidity distance between D^0 and \bar{D}^0 (left-bottom) and in $D^0 \bar{D}^0$ invariant mass (right-bottom) at LHCb, $\sqrt{S} = 7$ TeV. Green line represents the contribution of c -quark fragmentation, blue line – the gluon-fragmentation contribution, solid line is their sum. The LHCb data are from the Ref. [27].

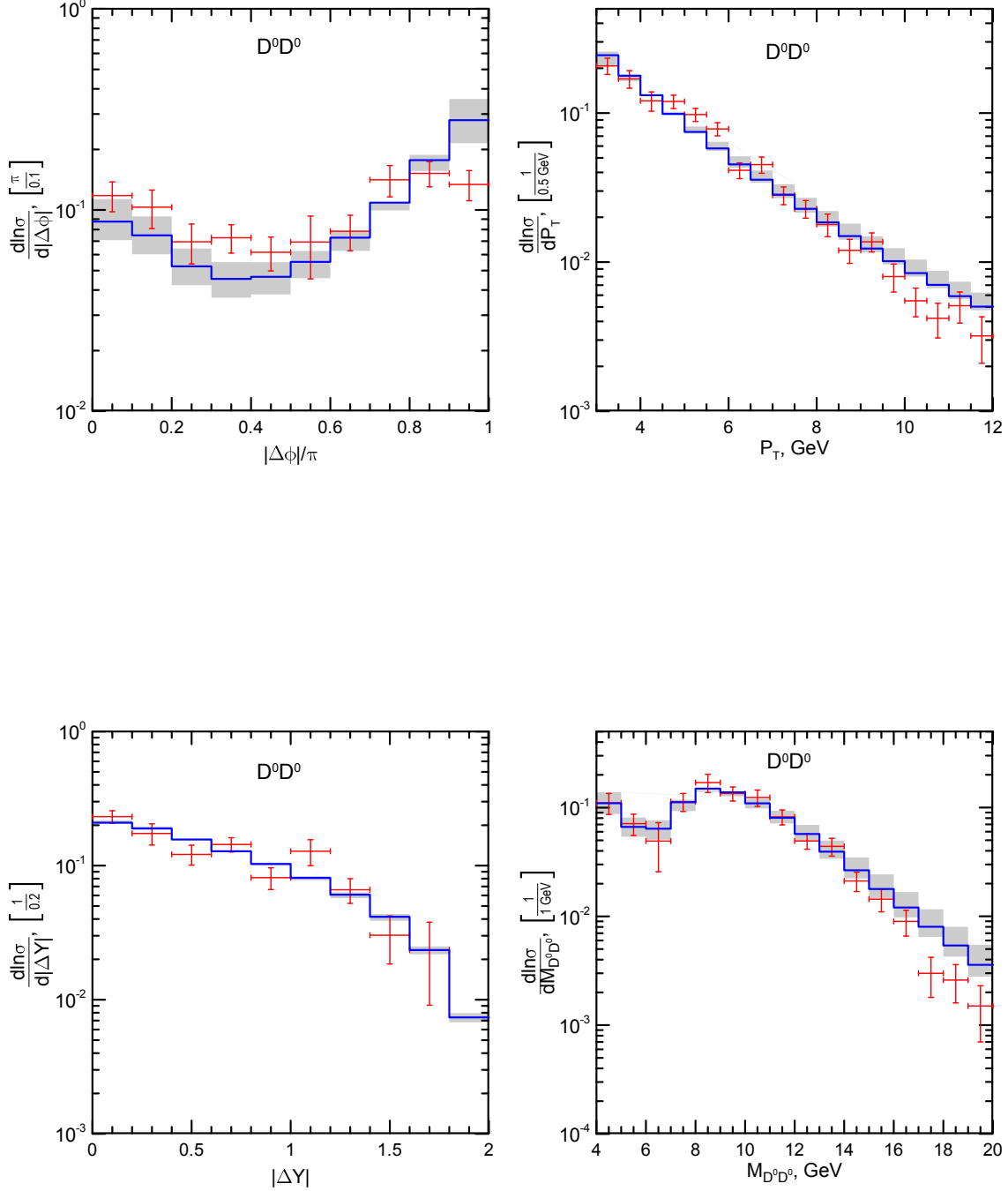


Figure 2: Distributions in azimuthal angle between D^0 and \bar{D}^0 mesons (left-top); in transverse momentum of D^0 (right-top); in rapidity distance between D^0 and \bar{D}^0 (left-bottom) and in $D^0\bar{D}^0$ invariant mass (right-bottom) at LHCb, $\sqrt{s} = 7$ TeV. The blue line represents the gluon-fragmentation contribution. The LHCb data are from the Ref. [27].